

*Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring*  
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*B.M. Peterson, R.S. Polidan, and R.W. Pogge*

## Variability in LINERs

J. C. Shields<sup>1</sup>, H.-W. Rix<sup>2</sup>, D. H. McIntosh<sup>3</sup>, L. C. Ho<sup>4</sup>, G. Rudnick<sup>3</sup>,  
 A. V. Filippenko<sup>5</sup>, W. L. W. Sargent<sup>6</sup>, M. Sarzi<sup>2,7</sup>, and M. Eracleous<sup>8</sup>

<sup>1</sup>*Ohio University, Physics & Astronomy Dept, Athens, OH 45701*

<sup>2</sup>*Max-Planck-Institut für Astronomie, Heidelberg, Germany*

<sup>3</sup>*Steward Observatory, University of Arizona, Tucson, AZ 85721*

<sup>4</sup>*Obs. of the Carnegie Institution of Washington, Pasadena, CA 91101*

<sup>5</sup>*University of California, Astronomy Dept, Berkeley, CA 94720-3411*

<sup>6</sup>*Palomar Observatory, Caltech 105-24, Pasadena, CA 91125*

<sup>7</sup>*Università di Padova, Dpto. di Astronomia, Padova, Italy*

<sup>8</sup>*Pennsylvania State University, Astronomy & Astrophysics,  
 University Park, PA 16802*

**Abstract.** A small number of LINERs have been seen to display variable H $\alpha$  emission with a very broad, double-peaked profile. Recent observations with the *Hubble Space Telescope* indicate that such emission may be a common attribute of LINERs. The double-peaked or double-shouldered line profiles resemble those found in a subset of broad-line radio galaxies. Several lines of argument suggest that such features trace an outer thin accretion disk irradiated by an inner ion torus, in accord with advection-dominated accretion flow (ADAF) models. Variability monitoring of this broad H $\alpha$  component thus may provide a means of testing accretion physics on small scales within these sources.

## 1. Introduction

Low Ionization Nuclear Emission-line Regions (LINERs; Heckman 1980) are found in approximately 30% of bright galaxies (Ho, Filippenko, & Sargent 1997a). While LINERs may form a heterogeneous class in terms of excitation mechanisms (e.g., Filippenko 1996), an important fraction are clearly weak manifestations of quasar-like phenomena, as demonstrated by the presence of broad H $\alpha$  emission in  $\gtrsim 20\%$  of these sources (Ho et al. 1997b).

LINERs also vary in their luminous output, although rather little is known about this aspect of their behavior. Continuum variability has been reported at radio (e.g., Heeschen & Puschell 1983; Ho et al. 1999b) and X-ray (e.g., Ho et al. 1999a) wavelengths, but the data are limited to individual objects or small samples, observed with very limited temporal coverage. Measurement of variability in the optical continuum is severely hampered by the weakness of the

AGN continuum relative to the starlight from the surrounding bulge. Broad  $H\alpha$  emission, when present, is also visible primarily as wings on the  $H\alpha + [\text{N II}]$  narrow-line blend, requiring a careful decomposition and continuum subtraction to measure accurately.

Monitoring of broad  $H\alpha$  emission has been carried out for a few LINERs, and suggests that variability in this feature is often weak or absent (e.g., Ho, Filippenko, & Sargent 1996). However, variability of a dramatic nature, involving the appearance of a broad, double-peaked line component, has been reported in three objects: NGC 1097 (Storchi-Bergmann, Baldwin, & Wilson 1993), Pictor A (Halpern & Eracleous 1994; Sulentic et al. 1995), and M81 (Bower et al. 1996). If this behavior is characteristic of LINERs, the nature of this emission component and its temporal evolution may hold important clues to the underlying accretion structure.

## 2. New Results from HST

New results that bear on accretion processes in LINERs have recently emerged from a Survey of Nearby Nuclei with STIS (SUNNS; Rix et al. 2000). Under this program, optical long-slit spectra of 24 nearby, weakly active galaxy nuclei were obtained in order to study the gas kinematics and ionization properties on small scales (resolution  $\approx 0.1''$ ). A surprise that emerged from this work was the discovery of ultra-broad  $H\alpha$  emission in NGC 4203 and NGC 4450 (Figure 1). Both of these objects were classified from ground-based spectra as LINER 1.9 sources (i.e., showing indications of broad  $H\alpha$ ; Ho et al. 1997b), but the *Hubble Space Telescope* (*HST*) spectra reveal for the first time emission components showing double peaks or shoulders, separated by  $\sim 7000 \text{ km s}^{-1}$  in velocity (Shields et al. 2000; Ho et al. 2000). A similar finding based on *HST* observations of the LINER NGC 4579 has recently been reported by Barth et al. (2000). These emission components bear a strong resemblance to the variable double-peaked emission reported in the past for some other LINERs (§1).

## 3. Double-Peaked Emission

Double-peaked  $H\alpha$  emission similar to that found in LINERs has been studied previously in other AGNs, notably in a subset of broad-line radio galaxies (BLRGs; Eracleous & Halpern 1994). Double-peaked lines in general are suggestive of emission from a rotating disk, and the  $H\alpha$  profiles in BLRGs have been successfully reproduced in a number of cases with relativistic accretion disk models (e.g., Chen & Halpern 1989; Eracleous & Halpern 1994). This interpretation is not unique, with alternative explanations including emission from bipolar outflows, and from gas associated with binary black holes (Eracleous 1999 and references therein). However, the accretion disk model remains attractive for several reasons, including its ability to explain several characteristic asymmetries of the line profiles that can naturally be ascribed to relativistic effects.

Why would some accretion disks exhibit pronounced emission in the Balmer lines, while others do not? One explanation comes from theoretical models of accretion flows described by small accretion rates ( $\dot{M}$ ), relative to the Eddington

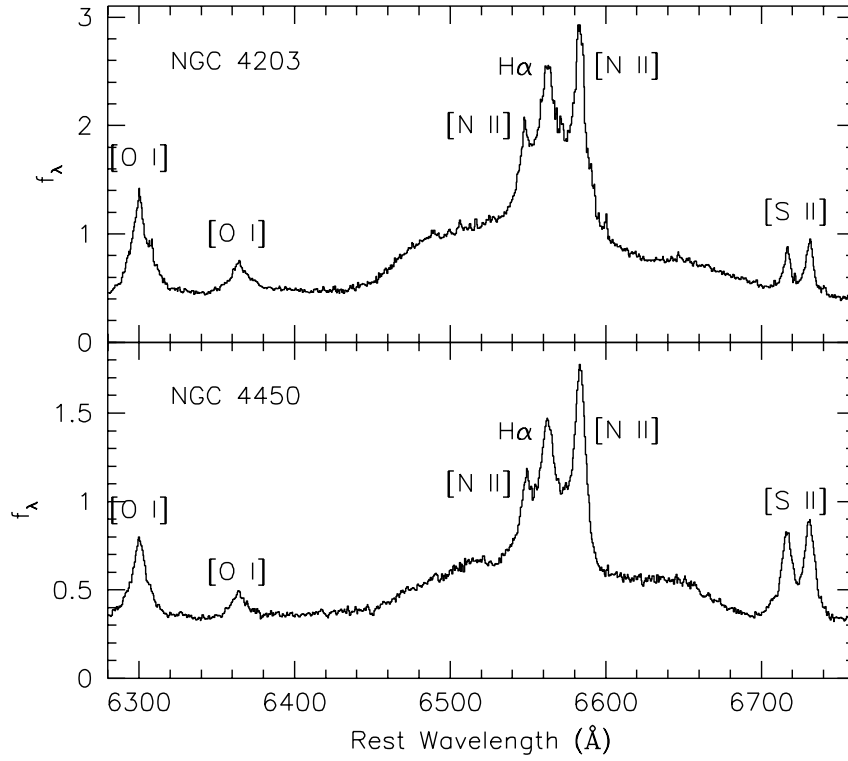


Figure 1. STIS spectra of the central  $0''.25 \times 0''.2$  for the LINERs NGC 4203 and NGC 4450. Flux densities are in units of  $10^{-15}$  ergs  $s^{-1} cm^{-2} \text{Å}^{-1}$ .

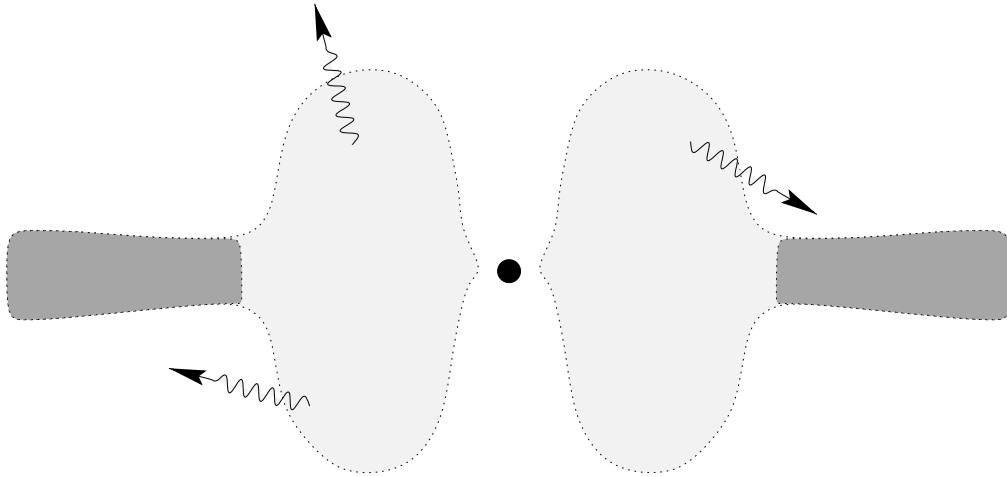


Figure 2. Cartoon cross-section showing a black hole encircled by an ion torus, with the latter irradiating an outer thin disk. In this picture the outer disk produces the observed double-peaked  $H\alpha$  emission.

value (Rees et al. 1982; Chen & Halpern 1989). In these scenarios, ions in the inner disk cool inefficiently and become very hot; the resulting high pressure produces a puffed-up structure, or “ion torus,” with nearly spherical inflow. Most of the thermal accretion energy of the torus is carried into the black hole, rather than being emitted as radiation, in contrast with the expected behavior of thin disks. As a source of energetic photons, however, the torus may nonetheless be important for irradiating an outer disk that remains thin (Figure 2). Reprocessing of this energy may then give rise to the double-peaked emission. Sources with higher  $\dot{M}$  would retain a thin disk and no torus, so that the added external illumination and double-peaked emission would be absent.

This scenario fits well, at least in qualitative terms, with the Advection Dominated Accretion Flow (ADAF) models discussed in detail at this meeting by Narayan and Quataert. The low luminosity of LINERs is logically consistent with a low accretion rate and radiative efficiency. X-ray monitoring of LINERs also reveals weak variability in these systems in comparison with Seyfert nuclei, a result in accord with ADAFs, for which the X-ray source is characteristically larger than in thin-disk accretion sources (Ptak et al. 1998).

#### 4. Variability

A natural question concerning the SUNNS discovery of double-peaked LINER emission is whether this finding stems from variability, as in the previous cases reported from the ground. An alternative explanation is that the double-shouldered emission was found because of the substantial diminution of background starlight in the *HST* aperture in comparison with ground-based apertures. The necessity of removing the underlying stellar continuum presents a major difficulty in the measurement of emission components for these weak AGNs, using ground-based data.

The Palomar spectra of these sources published previously by Ho et al. (1997b) unfortunately do not provide an unambiguous answer, since wavelength-dependent focus variations render these data insensitive to the detection of ultra-broad emission components. However, the fact that *two* objects out of the (small) SUNNS sample exhibit this property suggests that the aperture effect, rather than propitious variability, is responsible.

While variability in NGC 4203 and NGC 4450 has not been demonstrated, there are nonetheless good reasons for monitoring these sources in the future in order to look for, and quantify, variability in the broad-line profile. Changes in the line profile can be used to gain information on characteristic time scales and dimensions for the accretion structure. In the LINER NGC 1097, the broad-line profile showed a reversal over time in the relative height of the red and blue peaks, indicating that asymmetries cannot be ascribed strictly to relativistic effects, which would favor a higher blue peak for a symmetric disk (Storchi-Bergmann et al. 1997). Optical monitoring of the nuclei of objects such as NGC 4203 and NGC 4450 will be challenging, but would be feasible under conditions of good seeing, with adaptive optics, or from space, such that background starlight is minimized. NGC 4203 is of particular interest in that the kinematics of resolved nebular emission surrounding the nucleus provide an upper limit on central black hole mass ( $< 5 \times 10^6 M_{\odot}$ ), with the promise of a measurement or

more stringent limit from future observations (Shields et al. 2000; Sarzi et al. 2000).

An easier task that is likely to be productive is to monitor the time evolution of broad emission in a sample of BLRGs that show similar line profiles in ground-based spectra. Initial efforts of this type have provided tantalizing indications of possible periodicities, and changes in the line profile consistent with an orbiting structure or wave in an accretion disk (Zheng, Veilleux, & Grandi 1991; Newman et al. 1997; Gilbert et al. 1999). As discussed in the next section, there are good reasons to think that conclusions drawn from monitoring luminous BLRGs may apply also to LINERs.

## 5. LINERs and BLRGs

Some LINERs and BLRGs share the common trait of double-shouldered  $H\alpha$ , but prototypes of each class contrast sharply in terms of their total power and radio properties. Heckman (1980) noted that LINERs are often associated with radio emission, but these sources tend to be weak cores (Nagar et al. 2000). In comparison, BLRGs often exhibit strong, extended jets and lobe emission, in addition to powerful cores. Does it make sense to view these disparate beasts as a common phenomenon?

Several pieces of evidence suggest that BLRGs and LINERs are, in fact, close cousins. BLRGs showing double-peaked emission have relatively strong low-ionization emission, in resemblance to LINERs (Eracleous & Halpern 1994). But perhaps more fundamentally, LINERs, like the BLRGs, are *radio-loud* sources. Observations with *HST* make it possible to separate out the AGN continuum from the background starlight in LINERs. Ho (1999) has recently used such data, in conjunction with other multiwavelength measurements, to assemble the broad-band spectral energy distributions (SEDs) for a sample of LINERs. The results, and radio/optical flux ratios, clearly demonstrate that LINERs more closely resemble luminous radio-loud AGNs than radio-quiet systems. Since LINERs are the most common form of active nucleus, and are mostly found in early-type disk galaxies (Ho et al. 1997a), this statement inverts two pieces of canonical wisdom concerning AGNs; i.e., when low-luminosity objects are included, (1) *the majority of AGNs are radio-loud*, and (2) *most radio-loud AGNs are found in disk galaxies*.

One notable aspect of LINER SEDs is that they are essentially missing the big blue bump (BBB) that is typical of luminous AGNs. (Note that the classification of LINERs as radio-loud systems is supported by the overall SED and not simply a relative weakness at optical wavelengths.) BLRGs with double-peaked emission lines also show indications of relatively weak BBB emission (Eracleous & Halpern 1994). The BBB is normally attributed to thermal emission from a geometrically thin accretion disk. The absence of this spectral feature can be understood in the framework of the ADAF model, in that the inner thin disk responsible for much of the short-wavelength optical/UV emission in luminous systems is missing when the ADAF is present (see Fig. 2).

## 6. Conclusions

The low luminosity of LINERs and their close association with the large bulges of early-type disk galaxies makes the study of their variability a challenging task in comparison with similar studies for Seyfert galaxies or quasars. Yet results for a handful of LINERs indicate that these sources do show variations in their broad lines, that appear predominantly in a double-peaked component. Results from the SUNNS survey suggest that such double-peaked emission may be a very common attribute of LINERs. This emission resembles that of more powerful BLRGs, and several lines of argument indicate that LINERs and BLRGs are related phenomena. Accretion via an ADAF encircled by a residual thin disk provides a very appealing phenomenological explanation for the properties of these objects, in which case the broad H $\alpha$  emission acts as a direct tracer of the accretion structure. These results provide a strong motivation for future variability monitoring of LINERs and BLRGs, in order to probe the structure of these systems and test physical models of the accretion process.

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